US009382862B2

(12) **United States Patent**
Chen et al.

(10) **Patent No.: US 9,382,862 B2**
(45) **Date of Patent: Jul. 5, 2016**

(54) **AIR-FUEL PARAMETER CONTROL SYSTEM, METHOD AND CONTROLLER FOR COMPENSATING FUEL FILM DYNAMICS**

(71) Applicant: **NATIONAL TAIPEI UNIVERSITY of TECHNOLOGY**, Taipei (TW)

(72) Inventors: **Bo-Chiuan Chen**, Taipei (TW); **Yuh-Yih Wu**, Taipei (TW); **Wen-Han Tsai**, Taoyuan County (TW); **Hsien-Chi Tsai**, Kaohsiung (TW)

(73) Assignee: **NATIONAL TAIPEI UNIVERSITY of TECHNOLOGY**, Taipei (TW)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 268 days.

(21) Appl. No.: **14/318,679**

(22) Filed: **Jun. 29, 2014**

(65) **Prior Publication Data**

US 2015/0377170 A1 Dec. 31, 2015

(51) **Int. Cl.**

F02D 41/30 (2006.01)
F02D 41/24 (2006.01)
F02D 41/04 (2006.01)
F02D 41/14 (2006.01)
F02D 41/18 (2006.01)

(52) **U.S. Cl.**

CPC ***F02D 41/2477*** (2013.01); ***F02D 41/047*** (2013.01); *F02D 41/1456* (2013.01); *F02D 41/18* (2013.01); *F02D 41/2451* (2013.01); *F02D 2041/1417* (2013.01); *F02D 2200/0614* (2013.01)

(58) **Field of Classification Search**

CPC ... F02D 41/30; F02D 41/3005; F02D 41/047; F02D 41/2477; F02D 41/18; F02D 41/1456; F02D 2041/1417

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,667,640 A *	5/1987	Sekozawa	F02D 41/047 123/480
4,852,538 A *	8/1989	Nagaishi	F02D 41/107 123/480
4,953,530 A *	9/1990	Manaka	F02D 41/047 123/399
5,404,856 A *	4/1995	Servati	F02D 41/047 123/478
6,856,889 B2 *	2/2005	Nagaishi	F02D 35/025 123/435

FOREIGN PATENT DOCUMENTS

JP 61061940 A * 3/1986 .... F02D 41/06

* cited by examiner

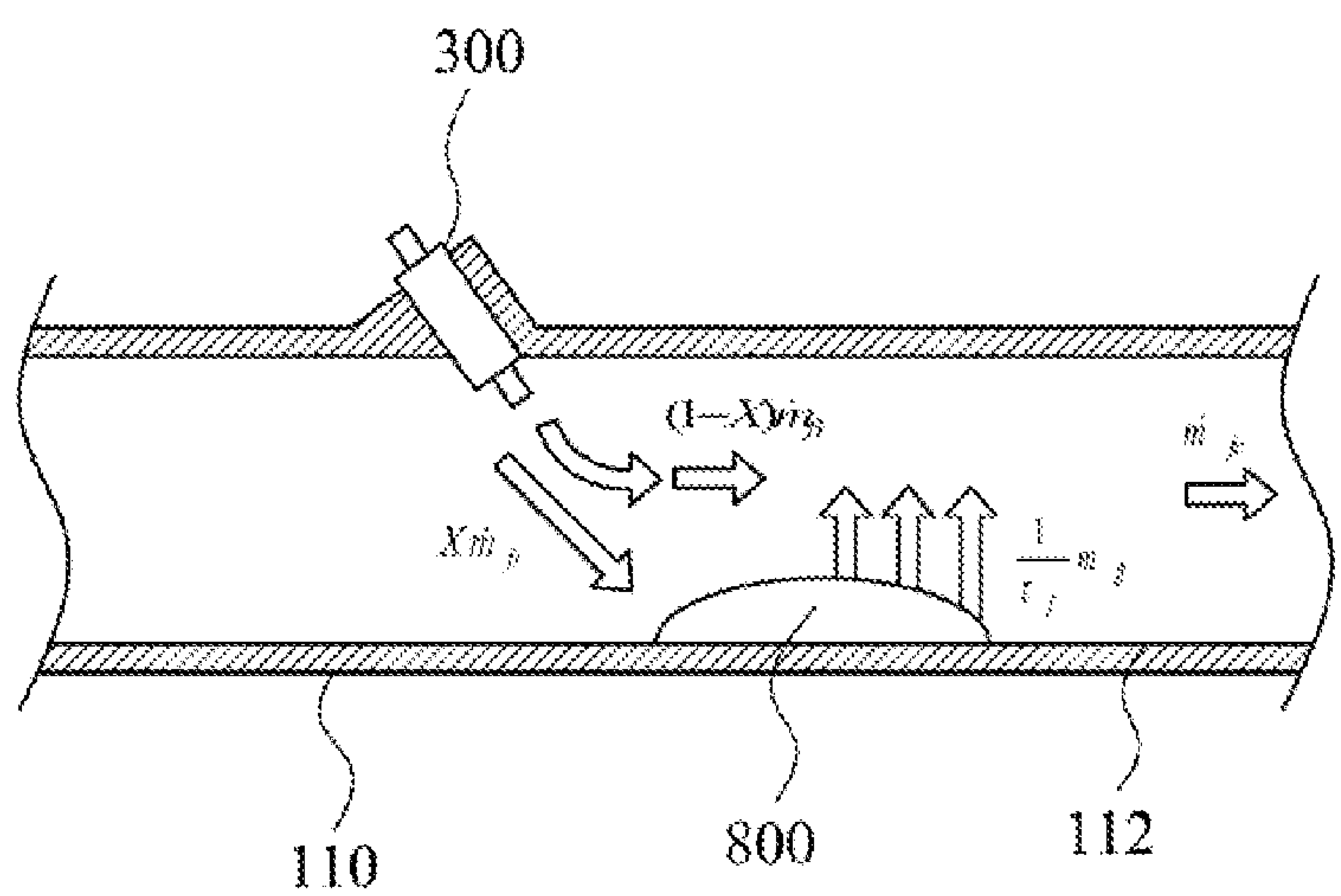
Primary Examiner — Hieu T Vo

(74) *Attorney, Agent, or Firm* — CKC & Partners Co., Ltd.

(57) **ABSTRACT**

An air-fuel parameter control system includes an injector, an air-fuel parameter sensor, a fuel film parameter calculation module, an air-fuel parameter prediction module and a fuel injection calibration module. The injector injects fuel into an intake manifold. The air-fuel parameter sensor detects a detected air-fuel parameter in an exhaust pipe. The fuel film parameter calculation module calculates a fuel film parameter relating to a fuel film accumulated the intake manifold based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine. The air-fuel parameter prediction module predicts a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter. The fuel injection calibration module calibrates the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

18 Claims, 3 Drawing Sheets



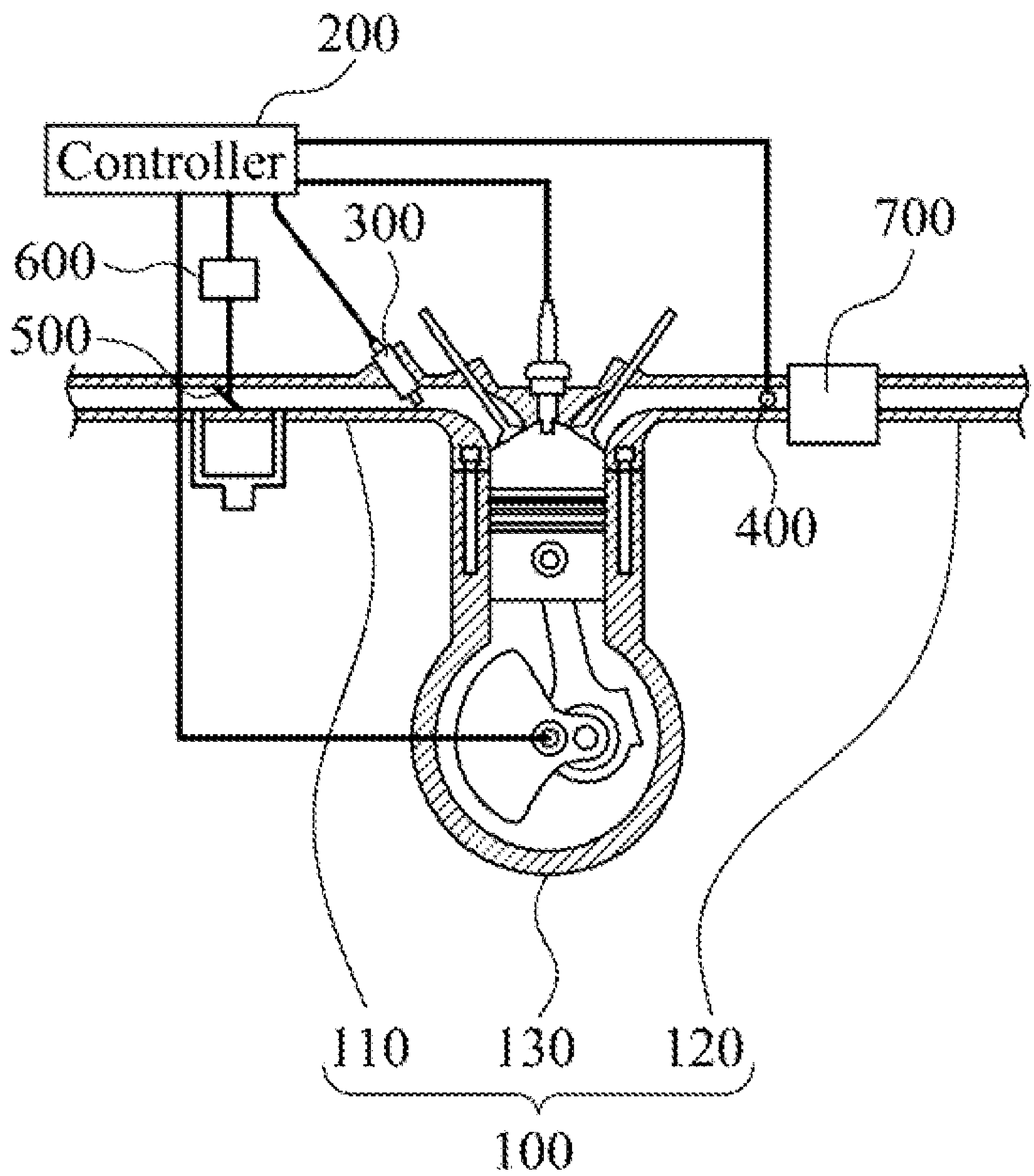

200
Controller
300
600
500
700
400
110
130
120
100

Fig. 1

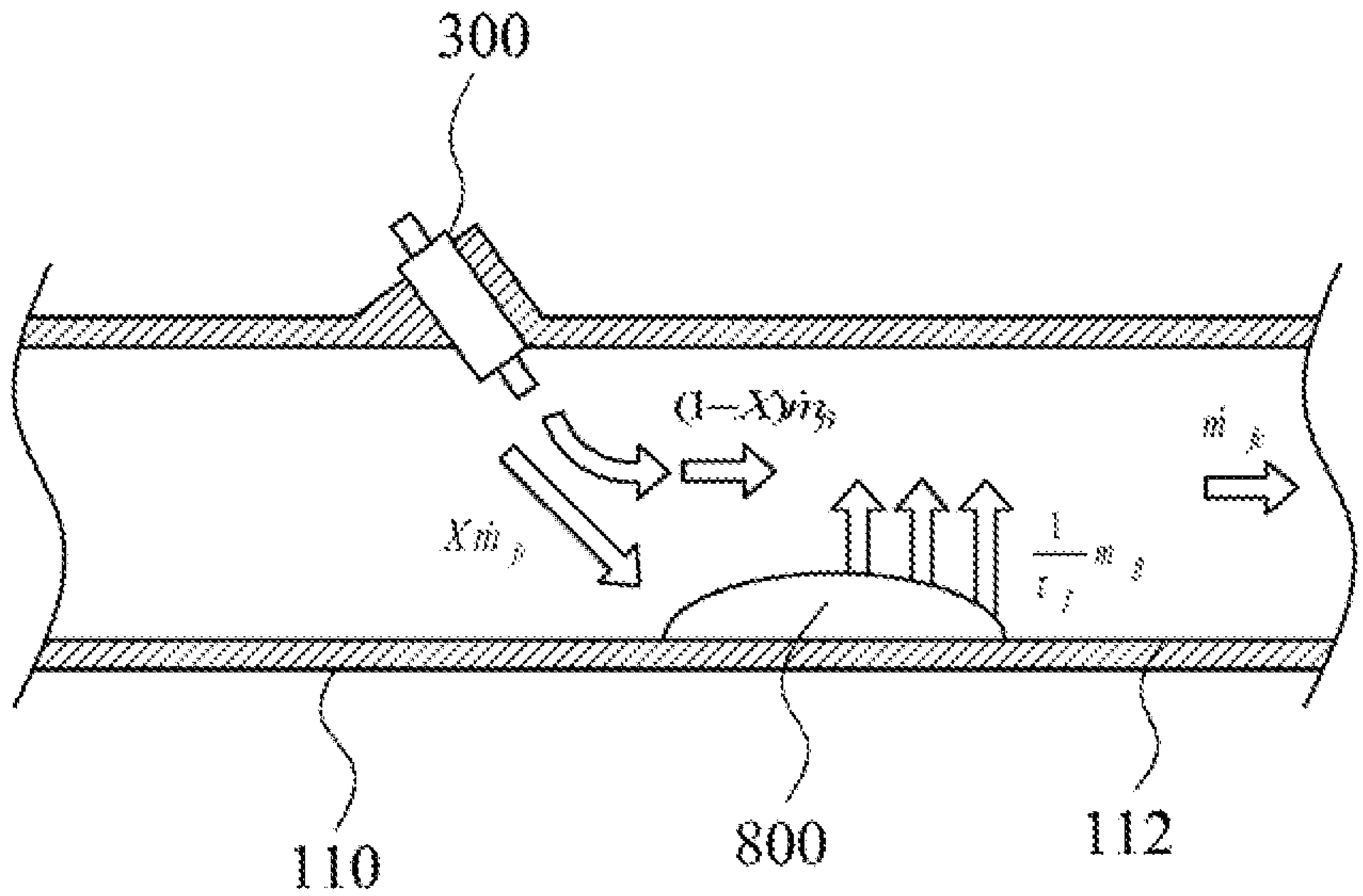

300
110
800
112

Fig. 2

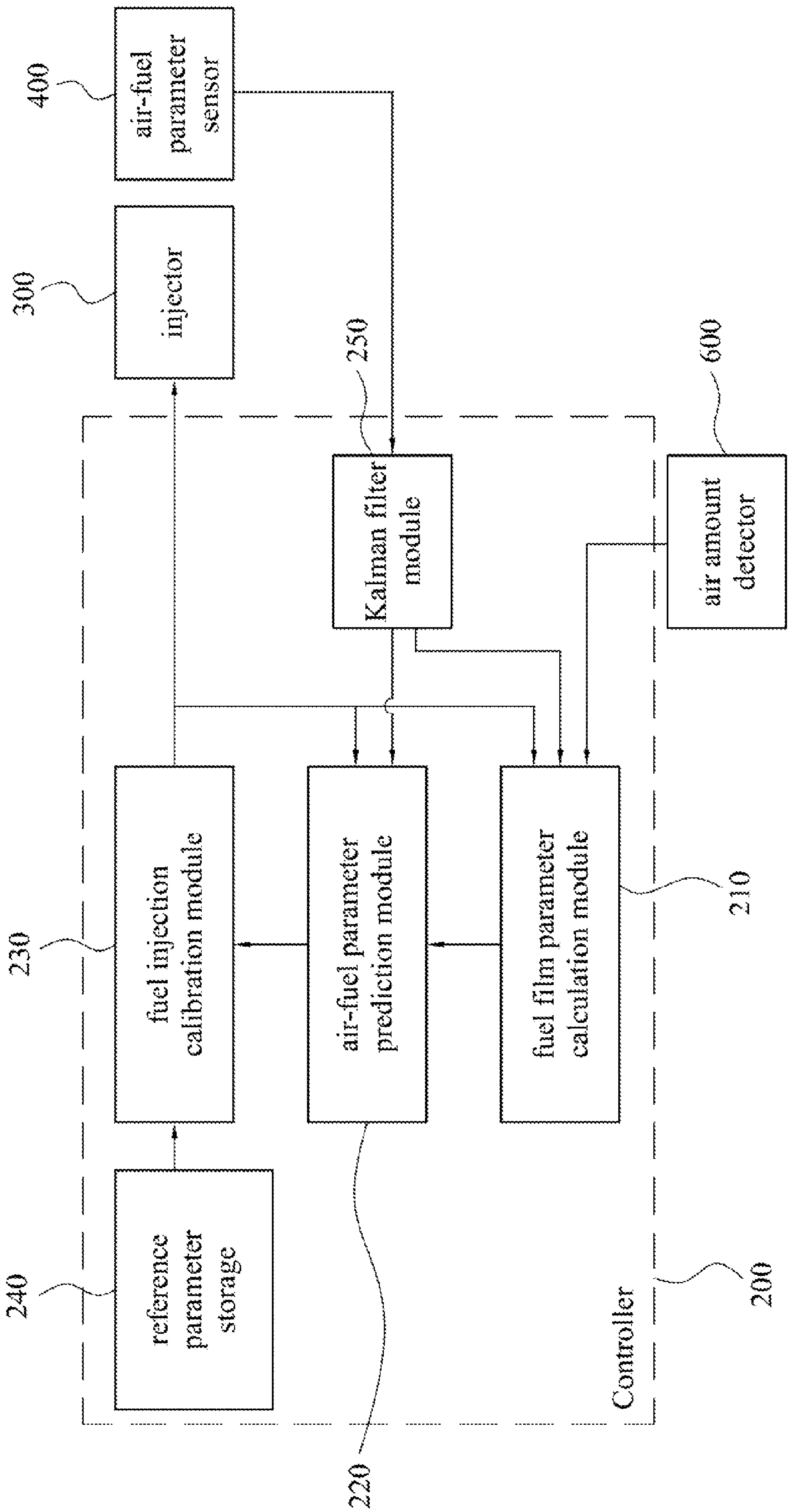

400
air-fuel parameter sensor
300
injector
250
Kalman filter module
600
air amount detector
230
fuel injection calibration module
air-fuel parameter prediction module
fuel film parameter calculation module
210
240
reference parameter storage
Controller
200
220

Fig. 3

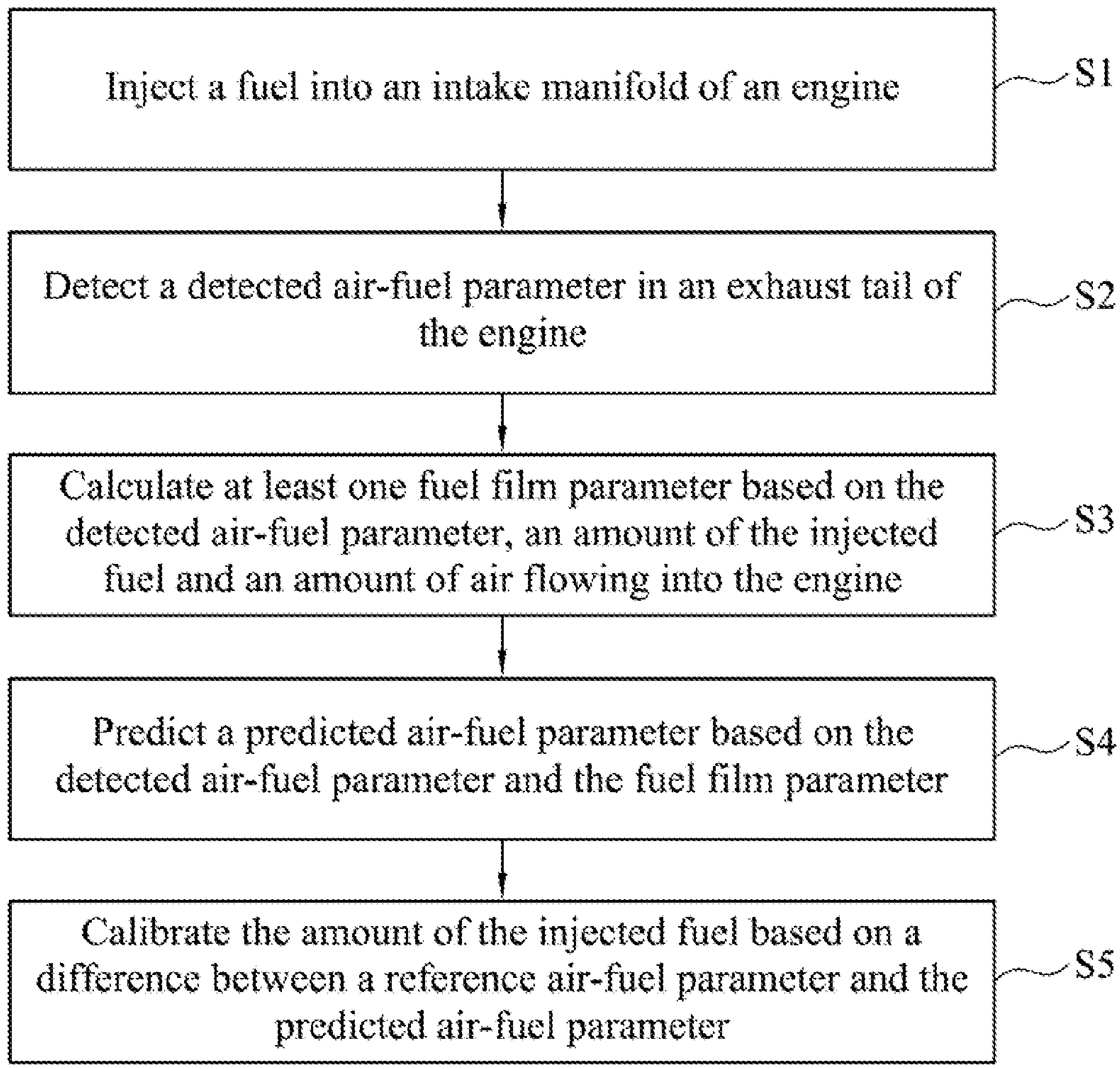

Inject a fuel into an intake manifold of an engine
S1
Detect a detected air-fuel parameter in an exhaust tail of the engine
S2
Calculate at least one fuel film parameter based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine
S3
Predict a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter
S4
Calibrate the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter
S5

Fig. 4

AIR-FUEL PARAMETER CONTROL SYSTEM, METHOD AND CONTROLLER FOR COMPENSATING FUEL FILM DYNAMICS

BACKGROUND

1. Technical Field

Embodiments of the present invention relate to air-fuel control. More particularly, embodiments of the present invention relate to the air-fuel parameter control system, method and controller for compensating fuel film dynamics.

2. Description of Related Art

When a typical spark-ignition engine is operating, the toxic gases, such as CO, HC and No_x, are produced. The toxic gases can be converted to non-toxic gases by a three-way catalyst converter. When the air-fuel ratio reaches the stoichiometric air-fuel ratio, the catalyst conversion efficiency can be optimized, which minimizes the toxic gases. As a result, the air-fuel ratio not only affects the engine performance, but also affects the exhaust toxic gases. Therefore, air-fuel ratio control plays an important role in the engine management system.

The air-fuel ratio can be easily controlled to reach the stoichiometric air-fuel ratio when the engine operates in a steady state. However, when operation of the engine varies rapidly, such as quickly opening the throttle, the air-fuel ratio varies severely, which is unfavorable for reaching the stoichiometric air-fuel ratio.

SUMMARY

A summary of certain embodiments disclosed herein is set forth below. It should be understood that these aspects are presented merely to provide the reader with a brief summary of these certain embodiments and that these aspects are not intended to limit the scope of this disclosure. Indeed, this disclosure may encompass a variety of aspects that may not be set forth below.

One aspect of the present invention is to control the air-fuel ratio to reach the stoichiometric air-fuel ratio even if operation of the engine varies rapidly.

In accordance with one embodiment of the present invention, an air-fuel parameter (such as the air-fuel ratio) control system for compensating fuel film dynamics includes an injector, an air-fuel parameter sensor, a fuel film parameter calculation module, an air-fuel parameter prediction module and a fuel injection calibration module. The injector is configured for injecting fuel into an intake manifold of an engine. The air-fuel parameter sensor is configured for detecting a detected air-fuel parameter in an exhaust pipe of the engine. The fuel film parameter calculation module is configured for calculating at least one fuel film parameter relating to a fuel film accumulated on an inner wall of the intake manifold based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine. The air-fuel parameter prediction module is configured for predicting a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter. The fuel injection calibration module is configured for calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

In accordance with another embodiment of the present invention, an air-fuel parameter control method for compensating fuel film dynamics is provided, including the following steps. Fuel is injected into an intake manifold of an engine. A detected air-fuel parameter in an exhaust pipe of the engine is detected. At least one fuel film parameter relating to a fuel film accumulated on an inner wall of the intake manifold is calculated based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine. A predicted air-fuel parameter is predicted based on the detected air-fuel parameter and the fuel film parameter. The amount of the injected fuel is calibrated based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

In accordance with yet another embodiment of the present invention, a controller for compensating fuel film dynamics is provided, which includes a fuel film parameter calculation module, an air-fuel parameter prediction module and a fuel injection calibration module. The fuel film parameter calculation module is configured for calculating at least one fuel film parameter relating to a fuel film accumulated on an inner wall of an intake manifold of an engine based on a detected air-fuel parameter, an amount of an injected fuel injected into the engine and an amount of air flowing into the engine. The air-fuel parameter prediction module is configured for predicting a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter. The fuel injection calibration module is configured for calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

In the foregoing embodiments, the air-fuel parameter control system and method takes the fuel film accumulated on the inner wall of the intake manifold into consideration, in which the fuel film may affect the air-fuel parameter in the exhaust pipe when operation of the engine varies rapidly. As a result, even though operation of the engine varies rapidly, the air-fuel ratio in the exhaust pipe can still be controlled to reach the stoichiometric air-fuel ratio.

It is to be understood that both the foregoing general description and the following detailed description are by examples, and are intended to provide further explanation of the invention as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention can be more fully understood by reading the following detailed description of the embodiment, with reference made to the accompanying drawings as follows:

FIG. **1** is a cross-sectional view of an engine in accordance with one embodiment of the present invention; and

FIG. **2** is an enlarged fragmentary view of the engine in FIG. **1**;

FIG. **3** is a block diagram of the air-fuel parameter control system in accordance with one embodiment of the present invention; and

FIG. **4** is a flow chart of the air-fuel parameter control method for compensating fuel film dynamics in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION

Reference will now be made in detail to the present embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers are used in the drawings and the description to refer to the same or like parts. In the whole context, the term "air-fuel parameter" means the air-fuel ratio or the fuel-air equivalence ratio.

FIG. **1** is a cross-sectional view of an engine **100** in accordance with one embodiment of the present invention. As shown in FIG. **1**, the engine **100** includes an intake manifold

110, an exhaust pipe **120** and a cylinder **130**. The intake manifold **110** and the exhaust pipe **120** are fluidly connected to opposite sides of the cylinder **130**. An injector **300** is disposed in the intake manifold **110** to inject fuel into the intake manifold **110**. A throttle **500** is disposed in the intake manifold **110**, and it allows air flowing into the intake manifold **110** and controls the amount of the air flowing into the intake manifold **110** as well. An air amount detector **600** is coupled to the throttle **500** to detect the amount of the air flowing into the intake manifold **110**. A three-way catalyst converter **700** is disposed in the exhaust pipe **120** for converting toxic gases to non-toxic gases when the engine **100** is in operation. An air-fuel parameter sensor **400** is disposed in the exhaust pipe **120** to detect a detected air-fuel parameter in the exhaust pipe **120** of the engine **100**. The conversion efficiency of the three-catalyst converter **700** can be optimized by controlling the air-fuel ratio in the exhaust pipe **120** to reach the stoichiometric air-fuel ratio. However, the air-fuel ratio cannot be easily controlled when operation of the engine **100** varies rapidly.

In some embodiments of the present invention, it is found that the reason why the air-fuel ratio cannot be easily controlled when operation of the engine **100** varies rapidly is due to the fuel film dynamics in the intake manifold **110**. More particularly, reference can be now made to FIG. **2**, which is an enlarged fragmentary view of the engine **100** in FIG. **1**. As shown in FIG. **2**, when the injector **300** injects the fuel into the intake manifold **110**, a part of the fuel may be accumulated on an inner wall **112** of the intake manifold **110** to form the fuel film **800**. When the engine **100** is in steady operation, the fuel film **800** has a steady thickness, so that the fuel film does not affect the air-fuel ratio significantly. However, when operation of the engine **100** varies rapidly, the fuel film **800** varies severely and does not have a steady thickness. In other words, the fuel film **800** may become thicker or thinner when operation of the engine **100** varies rapidly, which affects the air-fuel ratio, whereby making control for the air-fuel ratio difficult.

As a result, embodiments of the present invention provide a control system that controls the air-fuel parameter, such as the air-fuel ratio, in consideration of the dynamics of the fuel film **800**. Reference can be now made to FIG. **3**, which is a block diagram of the air-fuel parameter control system in accordance with one embodiment of the present invention. As shown in FIG. **3**, the air-fuel control system includes a controller **200**, the injector **300**, and an air-fuel parameter sensor **400**. The controller **200** includes a fuel film parameter calculation module **210**, an air-fuel parameter prediction module **220**, a fuel injection calibration module **230** and a reference parameter storage **240**. The fuel film parameter calculation module **210** is configured for calculating at least one fuel film parameter relating to the fuel film **800** (See FIG. **2**) based on the detected air-fuel parameter detected by the air-fuel parameter sensor **400**, an amount of the injected fuel injected by the injector **300** and an amount of air flowing into the engine detected by the air amount detector **600**. The air-fuel parameter prediction module **220** is configured for predicting a predicted air-fuel parameter based on the detected air-fuel parameter detected by the air-fuel parameter sensor **400** and the fuel film parameter calculated by the fuel film parameter calculation module **210**. The reference parameter storage **240** stores a reference air-fuel parameter. The fuel injection calibration module **230** is configured for calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter stored in the reference parameter storage **240** and the predicted air-fuel parameter predicted by the air-fuel parameter prediction module **220**.

In such a controller **200**, because the fuel film parameter relating to the dynamics of the fuel film **800** is taken into consideration, the air-fuel parameter in the exhaust pipe **120** can be controlled to reach the reference air-fuel parameter even if operation of the engine **100** varies rapidly. For example, the air-fuel parameter can be the air-fuel ratio, and the controller **200** can control the air-fuel ratio in the exhaust pipe **120** to reach the stoichiometric air-fuel ratio even if operation of the engine **100** varies rapidly.

Fuel Film Parameter Calculation

In some embodiments, the fuel film parameter calculation module **210** is configured for calculating the fuel film parameter that includes a fuel accumulation ratio X and a time constant of fuel film evaporation τ_f. As shown in FIG. **2**, the fuel accumulation ratio X is a ratio of an amount of a part of the injected fuel that is accumulated on the inner wall **112** of the intake manifold **110** to an amount of the injected fuel. The time constant of fuel film evaporation τ_f relates to an evaporation speed of the fuel film **800**. By the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f, the air-fuel parameter prediction module **220** can predict the predicted air-fuel parameter in consideration of the fuel film dynamics.

A sampling period of the fuel film parameter calculation module **210** is equal to a period of an engine cycle T_s. In other words, the controller **200** utilizes an event-based structure to describe operation of the engine **100**. Regarding description of operation of the engine **100**, the event-based structure is more accurate than the time-based structure when operation of the engine **100** varies rapidly. In the event-based structure, the period of the engine cycle T_s substantially satisfies:

$$T_s=120/n_{cyl}N \quad \text{(Eq. 1)},$$

where n_{cyl} is a number of at least one cylinder **130** of the engine **100**, and N is a rotation speed of the engine **100**. The fuel film parameter calculation module **210** calculates the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f by an auto-regressive moving average (ARMA) model and a recursive least square (RLS) model. The detailed calculation of the fuel film parameter calculation module **210** is described as follows.

The dynamics of the fuel film **800** is shown in FIG. **2**. m_{ff} is the amount of the fuel film **800**, especially the mass of the fuel film **800**. $\dot{m}_{fc}$ is the flow rate of the fuel flowing into the cylinder **130** (See FIG. **1**), especially the fuel mass flow rate. The mass dynamics of the fuel film **800** substantially satisfies:

$$\dot{m}_{ff} = X\dot{m}_{fi} - \frac{1}{\tau_f}m_{ff}. \quad \text{(Eq. 2)}$$

The fuel mass flow rate of the fuel flowing into the cylinder **130** substantially satisfies:

$$\dot{m}_{fc} = (1 - X)\dot{m}_{fi} + \frac{1}{\tau_f}m_{ff}. \quad \text{(Eq. 3)}$$

The Laplace transfer function for Eq. 2 and Eq. 3 can be obtained, and then, a difference equation with emulation discretization is shown:

$$m_{fc}(k) - m_{fi}(k) = \left(1 - \frac{T_s}{\tau_f}\right)[m_{fc}(k-1) - m_{fi}(k-1)] + X[m_{fi}(k-1) - m_{fi}(k)]. \tag{Eq. 4}$$

A difference equation shown below describes the relation between the air-fuel ratio in the cylinder **130** (See FIG. **1**) and the air-fuel ratio in the exhaust pipe **120** after an engine cycle.

$$AFR_{cyl}(k-1) = AFR_{exh}(k) \tag{Eq. 5}$$

in which $AFR_{cyl}(k-1)$ is the air-fuel ratio during the intake stroke at "k" moment, and $AFR_{exh}(k)$ is the air-fuel ratio during the exhaust stroke at "k+1" moment. It is noted that in this context, the time interval between the "k" moment and the "k+1" moment is the period of the engine cycle T_s, so as to implement the event-based structure.

Next, the dynamic response between the actual air-fuel ratio and the detected air-fuel ratio detected by the air-fuel parameter sensor **400** are considered, and the transfer function in z-domain is shown:

$$G(z) = \frac{AFR_m(z)}{AFR_{exh}(z)} = \frac{\frac{T_s}{\tau_\lambda}}{z - 1 + \frac{T_s}{\tau_\lambda}}, \tag{Eq. 6}$$

in which AFR_m is the detected air-fuel ratio detected by the air-fuel parameter sensor **400**, and τ_λ is the response time constant of the air-fuel parameter sensor **400**.

Eq. 6 can be transferred into a difference equation, and Eq. 5 can be involved to the difference equation transferred from Eq. 6, so as to get the following equation:

$$AFR_{cyl}(k-2) = \frac{AFR_m(k) - \left(1 - \frac{T_s}{\tau_\lambda}\right)AFR_m(k-1)}{\frac{T_s}{\tau_\lambda}}. \tag{Eq. 7}$$

The fuel mass flow rate of the flue getting into the cylinder **130** can be expressed as:

$$m_{fc}(k-2) = \frac{m_{ac}(k-2)}{AFR_{cyl}(k-2)}, \tag{Eq. 8}$$

in which m_{ac} is the amount of air flowing into the engine **100**, especially the air mass of air flowing into the engine per engine cycle. In some embodiments, m_{ac} can be detected by the air amount detector **600**.

After combining Eq. 8 and Eq. 4, functions Y(k) and U(k) can be set as:

$$Y(k) = \frac{\frac{T_s}{\tau_\lambda} m_{ac}(k-2)}{AFR_m(k) - \left(1 - \frac{T_s}{\tau_\lambda}\right)AFR_m(k-1)} - m_{fi}(k-2); \tag{Eq. 9}$$

$$U(k) = m_{fi}(k-3) - m_{fi}(k-2), \tag{Eq. 10}$$

and the following equation can be obtained:

$$Y(k) = \left(1 - \frac{T_s}{\tau_f}\right)Y(k-1) + XU(k). \tag{Eq. 11}$$

The ARMA model can be utilized to rewrite Eq. 11 as:

$$Y(k) = \phi^T(k)\theta(k) \tag{Eq. 12}$$

in which $\phi(k)^T = [Y(k-1)\ U(k)]$ are known, and $\theta(k) = [a\ b]^T$ are the parameters to be determined. The RLS model can be utilized to identify the parameters a and b, in which

$$a = 1 - \frac{T_s}{\tau_f},\ b = X.$$

After recalculation the equations:

$$a = 1 - \frac{T_s}{\tau_f},\ b = X,$$

the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f can be obtained. In the foregoing calculation, the amount of air flowing into the engine m_{ac}, the detected air-fuel ratio AFR_m and the amount of the injected fuel m_{fi} are utilized to obtain the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f.

Air-Fuel Parameter Prediction

In some embodiments, the air-fuel parameter prediction module **220** and the fuel injection calibration module **230** can be performed by a model predictive controller. The air-fuel parameter prediction is described as follows. The air-fuel ratio of the engine **100** is represented as the fuel-air equivalence ratio as shown the following equation:

$$x(k+1) = Ax(k) + B\Delta u(k)$$

$$y(k) = Cx(k) \tag{Eq. 13}$$

in which A is the system matrix that satisfies:

$$A = \begin{bmatrix} \frac{-T_s}{\tau_f} & 0 & 0 \\ \frac{14.7}{m_{ac}} & 0 & 0 \\ 0 & 1 + \frac{T_s}{\tau_\lambda} & \frac{-T_s}{\tau_\lambda} \end{bmatrix},$$

and B is the input matrix that satisfies:

$$B = \begin{bmatrix} X\left(1 + \frac{T_s}{\tau_f}\right) \\ \frac{14.7(1-X)}{m_{ac}} \\ 0 \end{bmatrix},$$

and C is the output matrix that satisfies $C = [0\ 0\ 1]$, and x is the system state vector that satisfies $x = [m_{ff}\ \phi_e\ \phi_m]^T$. ϕ_e is the fuel-air equivalence ratio in the exhaust pipe **120**. $\#_m$ is the fuel-air equivalence ratio measured or detected by the air-fuel parameter sensor **400**. Δu is the system input that satisfies $\Delta u = m_{fc}$, and y is the system output that satisfies $y = \phi_m$. The fuel accumulation ratio X, the period of the engine cycle T_s, and the amount of air flowing into the engine m_{ac} are described in the foregoing "Fuel film parameter calculation", so they are not described repeatedly herein.

Eq. 13 can be transferred by generalized predictive control (GPC) into the following equation:

$$\hat{y}(k+j\mid k) = CA^j E[x(k)] + \sum_{i=0}^{j-1} CA^{j-i-1} B\Delta u(k+i), \qquad \text{(Eq. 14)}$$

in which j is the sampling number, and Eq. 14 can be transferred to the following equation when the sampling number "j" is 5:

$$\begin{bmatrix} \hat{y}(k+1\mid k) \\ \hat{y}(k+2\mid k) \\ \hat{y}(k+3\mid k) \\ \hat{y}(k+4\mid k) \\ \hat{y}(k+5\mid k) \end{bmatrix} = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \end{bmatrix} \begin{bmatrix} \hat{x}_1(k) \\ \hat{x}_2(k) \\ \hat{x}3(k) \end{bmatrix} + \qquad \text{(Eq. 15)}$$

$$\begin{bmatrix} CB & 0 & 0 & 0 & 0 \\ CAB & CB & 0 & 0 & 0 \\ CA^2B & CAB & CB & 0 & 0 \\ CA^3B & CA^2B & CAB & CB & 0 \\ CA^4B & CA^3B & CA^2B & CAB & CB \end{bmatrix} \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \Delta u(k+2) \\ \Delta u(k+3) \\ \Delta u(k+4) \end{bmatrix},$$

in which $\hat{y}(k+1|k)$ is the predicted system output (including the predicted air-fuel parameter) at the "k+1" moment which is calculated based on the detected air-fuel parameter and the fuel film parameter obtained at the "k" moment, and $\hat{y}(k+2|k)$ is the predicted system output at the "k+2" moment which is calculated based on the detected air-fuel parameter and the fuel film parameter obtained at the "k" moment, and so forth.

As a result, the air-fuel parameter prediction module **220** is operable to predict the predicted air-fuel parameter at the "k+j" moment represented by $\hat{y}(k+j|k)$ based on the detected air-fuel parameter x(k) and the fuel film parameters (including the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f) obtained at the "k" moment.

Fuel Injection Calibration

In some embodiments, the fuel injection calibration module **230** and the air-fuel parameter prediction module **220** can be performed by the model predictive controller (MPC), and the fuel injection calibration is described as follows.

Eq. 15 can be rewritten as:

$$y_{N12} = F_{N12}\hat{x}(k) + H_{N123}u_{N3} \qquad \text{(Eq. 16).}$$

The optimized cost function for the Eq. 16 can be expressed as:

$$J = (H_{123}u_{N3} + F_{N12}\hat{x}(k) - w)^T \bar{R}(H_{123}u_{N3} + F_{N12}\hat{x}(k) - w)\_n_{N3}{}^T \bar{Q} u_{N3} \qquad \text{(Eq. 17),}$$

in which w is the reference trajectory of the reference fuel-air equivalence ratio (i.e., the reference air-fuel parameter), and it satisfies

$$w = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix};$$

$\bar{Q}$ is the diagonal matrix that satisfies $\bar{Q}=1.5$, and it is used to control the error tolerance between the predicted air-fuel parameter and the reference air-fuel parameter; $\bar{R}$ is the diagonal matrix that satisfies

$$\bar{R} = \begin{bmatrix} 10 & 0 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 & 0 \\ 0 & 0 & 5.5 & 0 & 0 \\ 0 & 0 & 0 & 2.1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

and it can be adjusted based on the performance of the hardware of the controller **200**.

By partially differentiating Eq. 17, the optimized u can be obtained as:

$$u = ((H_{N123}{}^T \bar{R} H_{N123}) + \bar{Q})^{-1} H_{123}{}^T \bar{R}(w - F_{N12}\hat{x}(k)) \qquad \text{(Eq. 18).}$$

Based on Eq. 18, the system input "u" that represents fuel mass flowing into the cylinder **130** m_{fc} can be optimized to make the air-fuel parameter in the exhaust pipe **120** to reach the reference air-fuel parameter. As a result, the fuel injection calibration module **230** can calibrate the amount of the injected fuel according the optimized m_{fc} that is obtained based on a difference between the reference air-fuel parameter w and the predicted air-fuel parameter represented by $\hat{y}(k+j|k)$, so as to control the air-fuel parameter in the exhaust pipe **120** to reach the reference air-fuel parameter.

Kalman Filter

In some embodiments, when the air-fuel parameter sensor **400** is a narrow-band oxygen sensor, it may not provide a precise system state vector $x=[m_{ff}\ \phi_c\ \phi_m]^T$. As a result, as shown in FIG. **3**, in some embodiments, the controller **200** further includes a Kalman filter module **250** for providing a precise system state vector $x=[m_{ff}\ \phi_e\ \phi_m]^T$. In other words, the Kalman filter module **250** is configured for estimating an estimated wide-band air-fuel parameter based on the detected air-fuel parameter detected by the air-fuel parameter sensor **400**, so that the air-fuel parameter prediction module **220** can predict the predicted air-fuel parameter based on the estimated wide-band air-fuel parameter and the fuel film parameter.

The estimation model of the Kalman filter module **250** can be expressed as:

$$x_{k+1} = A_k\hat{x}_k + B_k u_k + \Gamma\xi_k$$

$$\hat{y}_k = C_k\hat{x}_k + v_k \qquad \text{(Eq. 19),}$$

in which $\hat{x}$ is the estimated system vector that satisfies $\hat{x}=[\hat{m}_{ff}\ \hat{\phi}_e\ \hat{\phi}_m]^T$. $\hat{y}$ is the estimated fuel-air equivalence ratio, i.e. the estimated wide-band air-fuel parameter, which satisfies $\hat{y}=\hat{\phi}_m$. u is m_{fc}. A_k, B_k, and C_k are the system matrices in Eq. 13 at the "k" moment. Γ is the system disturbance matrix. ξ is the ambient disturbance input. v is the noise of the air-fuel parameter sensor **400**.

When designing the Kalman filter, the discrete system may be verified whether it is fully observable or not with an observability matrix. After confirming the system is fully observable, the discrete Kalman filter can be designed, and the closed-loop estimator is expressed as the following equation:

$$\hat{x}_{k|k}=A_{k-1}\hat{x}_{k-1|k-1}+B_{k-1}u_{k-1}+G_k(y_k-\hat{y}_{k|k-1}) \quad \text{(Eq. 20)},$$

in which G is the Kalman gain and y_k is the detected fuel-air equivalence ratio detected by the air-fuel parameter sensor **400**. The algorithm can be separated into time update equations and measurement update equations. The time update equations provide the current state $\hat{x}_{k|k-1}$ and the error covariance $P_{k|k-1}$ to get the priori estimation for the next estimation. Measurement update equations are used for feedback correction. The original estimation and the new measurement state can be used to estimate more realistic state. As a result, the Kalman filter module **250** can estimate an estimated wide-band air-fuel parameter $\hat{x}_{k|k}$ based on the detected air-fuel parameter y_k.

When the air-fuel parameter prediction module **220** performs calculation in Eq. 14, E[x(k)] satisfies E[x(k)]=x̂(k). In other words, E[x(k)] is equal to the estimated wide-band air-fuel parameter estimated by the Kalman filter module **250**, so that the air-fuel parameter prediction module **220** can predict the predicted air-fuel parameter based on at least the estimated wide-band air-fuel parameter.

FIG. **4** is a flow chart of the air-fuel parameter control method for compensating fuel film dynamics in accordance with one embodiment of the present invention. As shown in FIG. **4**, in step S**1**, fuel is injected into the intake manifold **110** of the engine **100**. In particular, the injector **300** injects the fuel into the intake manifold **110**.

In step S**2**, The detected air-fuel parameter in the exhaust pipe **120** of the engine **100** can be detected. In particular, the air-fuel parameter sensor **400** detects the detected air-fuel parameter in the exhaust pipe **120** of the engine **100**.

In step S**3**, the fuel film parameter relating to the fuel film **800** accumulated on the inner wall **112** of the intake manifold **110** is calculated based on the detected air-fuel parameter, the amount of the injected fuel and the amount of air flowing into the engine. In particular, the fuel film parameter calculation module **210** utilizes the amount of air flowing into the engine m_{ac}, the detected air-fuel ratio AFR_m and the amount of the injected fuel m_{fi} to obtain the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f.

In step S**4**, the predicted air-fuel parameter is predicted based on the detected air-fuel parameter and the fuel film parameter. In particular, the air-fuel parameter prediction module **220** predicts the predicted air-fuel parameter at the "k+j" moment represented by ŷ(k+j|k) based on the detected air-fuel parameter x(k) and the fuel film parameters (including the fuel accumulation ratio X and the time constant of fuel film evaporation τ_f) obtained at the "k" moment.

In step S**5**, the amount of the injected fuel is calibrated based on a difference between the reference air-fuel parameter and the predicted air-fuel parameter. In particular, the fuel injection calibration module **230** calibrates the amount of the injected fuel based on a difference between the reference air-fuel parameter w and the predicted air-fuel parameter ŷ(k+j|k).

In some embodiments, when the air-fuel parameter sensor **400** is the narrow-band oxygen sensor, the estimated wide-band air-fuel parameter can be estimated based on the detected air-fuel parameter by a Kalman filter method, so that the air-fuel parameter prediction module **220** can predict the predicted air-fuel parameter based on a more precise estimated air-fuel parameter in the exhaust pipe **120**.

In the foregoing embodiments, the controller **200** can be, but is not limited to be, implemented by an integrated circuit or a processor installed with corresponding software or firmware that performs the fuel film parameter calculation module **210**, the air-fuel parameter prediction module **220**, the fuel injection calibration module **230** and the Kalman filter module **250**.

Although the present invention has been described in considerable detail with reference to certain embodiments thereof, other embodiments are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the embodiments contained herein.

It will be apparent to those skilled in the art that various modifications and variations can be made to the structure of the present invention without departing from the scope or spirit of the invention. In view of the foregoing, it is intended that the present invention cover modifications and variations of this invention provided they fall within the scope of the following claims.

What is claimed is:

1. An air-fuel parameter control system for compensating fuel film dynamics, comprising:

an injector for injecting fuel into an intake manifold of an engine;

an air-fuel parameter sensor for detecting a detected air-fuel parameter in an exhaust pipe of the engine;

a fuel film parameter calculation module for calculating at least one fuel film parameter relating to a fuel film accumulated on an inner wall of the intake manifold based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine;

an air-fuel parameter prediction module for predicting a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter; and

a fuel injection calibration module for calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

2. The air-fuel parameter control system of claim **1**, wherein a sampling period of the fuel film parameter calculation module is equal to a period of an engine cycle.

3. The air-fuel parameter control system of claim **2**, wherein the period of the engine cycle substantially satisfies:

$$T_s=\frac{120}{n_{cyl}N},$$

wherein T_s is the period of the engine cycle, and n_{cyl} is a number of at least one cylinder of the engine, and N is a rotation speed of the engine.

4. The air-fuel parameter control system of claim **1**, wherein the fuel film parameter calculation module is configured for calculating the fuel film parameter that comprises a fuel accumulation ratio and a time constant of fuel film evaporation based on the detected air-fuel parameter, the amount of the injected fuel and the amount of air flowing into the engine, wherein the fuel accumulation ratio is a ratio of an amount of a part of the injected fuel that is accumulated on the inner wall of the intake manifold to an amount of the injected fuel, wherein the time constant of fuel film evaporation relates to an evaporation speed of the fuel film.

5. The air-fuel parameter control system of claim 4, wherein the fuel film parameter calculation module is configured for calculating the fuel accumulation ratio and the time constant of fuel film evaporation by an auto-regressive moving average (ARMA) model and a recursive least square (RLS) model.

6. The air-fuel parameter control system of claim 1, wherein the air-fuel parameter sensor is a narrow-band oxygen sensor, and the air-fuel parameter control system further comprises:

a Kalman filter module for estimating an estimated wide-band air-fuel parameter based on the detected air-fuel parameter, wherein the air-fuel parameter prediction module is configured for predicting the predicted air-fuel parameter based on the estimated wide-band air-fuel parameter and the fuel film parameter.

7. A controller for compensating fuel film dynamics, comprising:

a fuel film parameter calculation module for calculating at least one fuel film parameter relating to a fuel film accumulated on an inner wall of an intake manifold of an engine based on a detected air-fuel parameter, an amount of an injected fuel injected into the engine and an amount of air flowing into the engine;

an air-fuel parameter prediction module for predicting a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter; and

a fuel injection calibration module for calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

8. The controller of claim 7, wherein a sampling period of the fuel film parameter calculation module is equal to a period of an engine cycle.

9. The controller of claim 8, wherein the period of the engine cycle substantially satisfies:

$$T_s = \frac{120}{n_{cyl}N},$$

wherein T_s is the period of the engine cycle, and n_{cyl} is a number of at least one cylinder of the engine, and N is a rotation speed of the engine.

10. The controller of claim 7, wherein the fuel film parameter calculation module is configured for calculating the fuel film parameter that comprises a fuel accumulation ratio and a time constant of fuel film evaporation based on the detected air-fuel parameter, the amount of the injected fuel and the amount of air flowing into the engine, wherein the fuel accumulation ratio is a ratio of an amount of a part of the injected fuel that is accumulated on the inner wall of the intake manifold to an amount of the injected fuel, wherein the time constant of fuel film evaporation relates to an evaporation speed of the fuel film.

11. The controller of claim 10, wherein the fuel film parameter calculation module is configured for calculating the fuel accumulation ratio and the time constant of fuel film evaporation by an auto-regressive moving average (ARMA) model and a recursive least square (RLS) model.

12. The controller of claim 7, further comprising:

a Kalman filter module for estimating an estimated wide-band air-fuel parameter based on the detected air-fuel parameter, wherein the air-fuel parameter prediction module is configured for predicting the predicted air-fuel parameter based on the estimated wide-band air-fuel parameter and the fuel film parameter.

13. An air-fuel parameter control method for compensating fuel film dynamics, comprising:

(a) injecting fuel into an intake manifold of an engine;

(b) detecting a detected air-fuel parameter in an exhaust pipe of the engine;

(c) calculating at least one fuel film parameter relating to a fuel film accumulated on an inner wall of the intake manifold based on the detected air-fuel parameter, an amount of the injected fuel and an amount of air flowing into the engine;

(d) predicting a predicted air-fuel parameter based on the detected air-fuel parameter and the fuel film parameter; and

(e) calibrating the amount of the injected fuel based on a difference between a reference air-fuel parameter and the predicted air-fuel parameter.

14. The air-fuel parameter control method of claim 13, wherein a sampling period of the step (c) is equal to a period of an engine cycle.

15. The air-fuel parameter control method of claim 14, wherein the period of the engine cycle substantially satisfies:

$$T_s = \frac{120}{n_{cyl}N},$$

wherein T_s is the period of the engine cycle, and n_{cyl} is a number of at least one cylinder of the engine, and N is a rotation speed of the engine.

16. The air-fuel parameter control method of claim 13, wherein the step (c) comprises:

calculating a fuel accumulation ratio and a time constant of fuel film evaporation based on the detected air-fuel parameter, the amount of the injected fuel and the amount of air flowing into the engine, wherein the fuel accumulation ratio is a ratio of an amount of a part of the injected fuel that is accumulated on the inner wall of the intake manifold to an amount of the injected fuel, wherein the time constant of fuel film evaporation relates to an evaporation speed of the fuel film.

17. The air-fuel parameter control method of claim 16, wherein the step (c) is performed by an auto-regressive moving average (ARMA) model and a recursive least square (RLS) model.

18. The air-fuel parameter control method of claim 13, further comprising:

estimating an estimated wide-band air-fuel parameter based on the detected air-fuel parameter by a Kalman filter method, wherein the predicted air-fuel parameter is predicted based on the estimated wide-band air-fuel parameter and the fuel film parameter.

* * * * *